

The decay of $^{209}_{86}\text{Rn}_{123}$ to levels in $^{209}_{85}\text{At}_{124}$

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Abstract

The decay of ^{209}Rn to levels in ^{209}At has been investigated. Gamma rays were studied in singles and coincidences using Ge(Li) detectors. Conversion electrons were recorded with a Si(Li) detector. A decay scheme is suggested, indicating electron capture branches to positive parity states at 1954, 2136 and 2415 keV. These states are interpreted in terms of core excitations in conformity with the ^{207}Bi isotone.

Two levels at 408 and 746 keV, tentatively assigned spin $7/2^-$, are fed by electron capture with $\log ft$ values of 6.8 and 6.4, respectively.

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1. Introduction

The decay of odd-A Po isotopes have recently been investigated in refs. [1, 2, 3]. One of the characteristic features of these decays is the electron capture which proceeds on one hand to $7/2^-$ -levels, on the other hand to positive parity states ($3/2^+$, $5/2^+$, ...). The $7/2^-$ levels may be interpreted as due to $\pi f_{7/2}$ and $\pi h_{9/2} \otimes 2^+$ -configurations. The positive parity states have been discussed in terms of proton core excitations [2,3]. It should be noted that the existence of these states at low energies is remarkable, seen in the context of the $h_{9/2} - s_{1/2}$ gap which is 4.2 MeV at the $Z = 82$ closure. It was therefore of interest to investigate whether states of the same type show up also in the decay of Rn isotopes.

In ^{211}At two positive parity states with spin 1/2 and 3/2 have been reported [4]. Both are fed in the beta decay. Another related nucleus to be compared with ^{209}At , is ^{207}Bi . Only one proton pair differs in these two cases. This should not mean any drastic changes for the positive parity states mentioned above. The levels of ^{207}Bi have been studied in refs. [1, 5]. Positron and electron capture decays were found to levels at 743 keV ($7/2^-$) with $\log ft = 7.4$ and 992 keV ($7/2^-$) with $\log ft = 6.5$. The positive parity states at 2060 keV ($3/2^+$) and 2405 keV ($5/2^+$) were populated with $\log ft = 6.2$, and 6.5, respectively.

Kempisty et al. [6] have studied the ^{209}Rn decay and found feeding to two states at 408 and 746 keV with tentatively assigned spin and parity $7/2^-$. They interpret the lower one as an $f_{7/2}$ level and the other one as being of $(h_{9/2}^3)_{7/2^-}$ -character.

The alpha branch (17%) populates levels [7] in ^{205}Po . Transitions in ^{205}Po are known from earlier experiments [8].

2. Experimental procedures and results

2.1. Source preparation

The experiment was performed at the ISOLDE facility [9] at CERN. A Th-target was bombarded with 600 MeV protons from the synchrocyclotron. The radon gas, produced in spallation reactions, was lead into the ion source of the electromagnetic isotope separator, where samples of ^{209}Rn were produced on backings of 14 mg/cm^2 Al. The contamination from neighbouring masses was normally less than 1%.

2.2. Gamma-ray spectroscopy

Successive spectra of ^{209}Rn sources were recorded with a 25 cm^3 Ge(Li) detector. The resolution (FWHM) was 1.9 - 2.2 keV for the energy region of interest. Fig. 1 shows a gamma spectrum obtained. Transitions assigned to the decay of ^{209}Rn to levels in ^{209}At are found in table 1. Also a "low-energy" spectrum (10-550 keV) was recorded using a 1 cm^3 Ge(Li) detector. No more transitions belonging to the ^{209}Rn decay were seen. The contributions from daughter products and from ^{210}Rn contamination could easily be identified from findings of earlier experiments [3, 10, 11]. Besides, the difference in half-lives compared to ^{209}Rn excludes a confusion. The ^{208}Rn contamination represents a more serious problem. No gamma spectrum of this decay was recorded. The assignments have therefore been made using the following information:

- a) Comparison with spectra from (heavily) contaminated ^{210}Rn sources where the ratio of $^{208}\text{Rn}/^{209}\text{Rn}$ intensities should differ from this experiment.
- b) Information from the coincidence measurement (see below).

Less certain transitions are given in table 2.

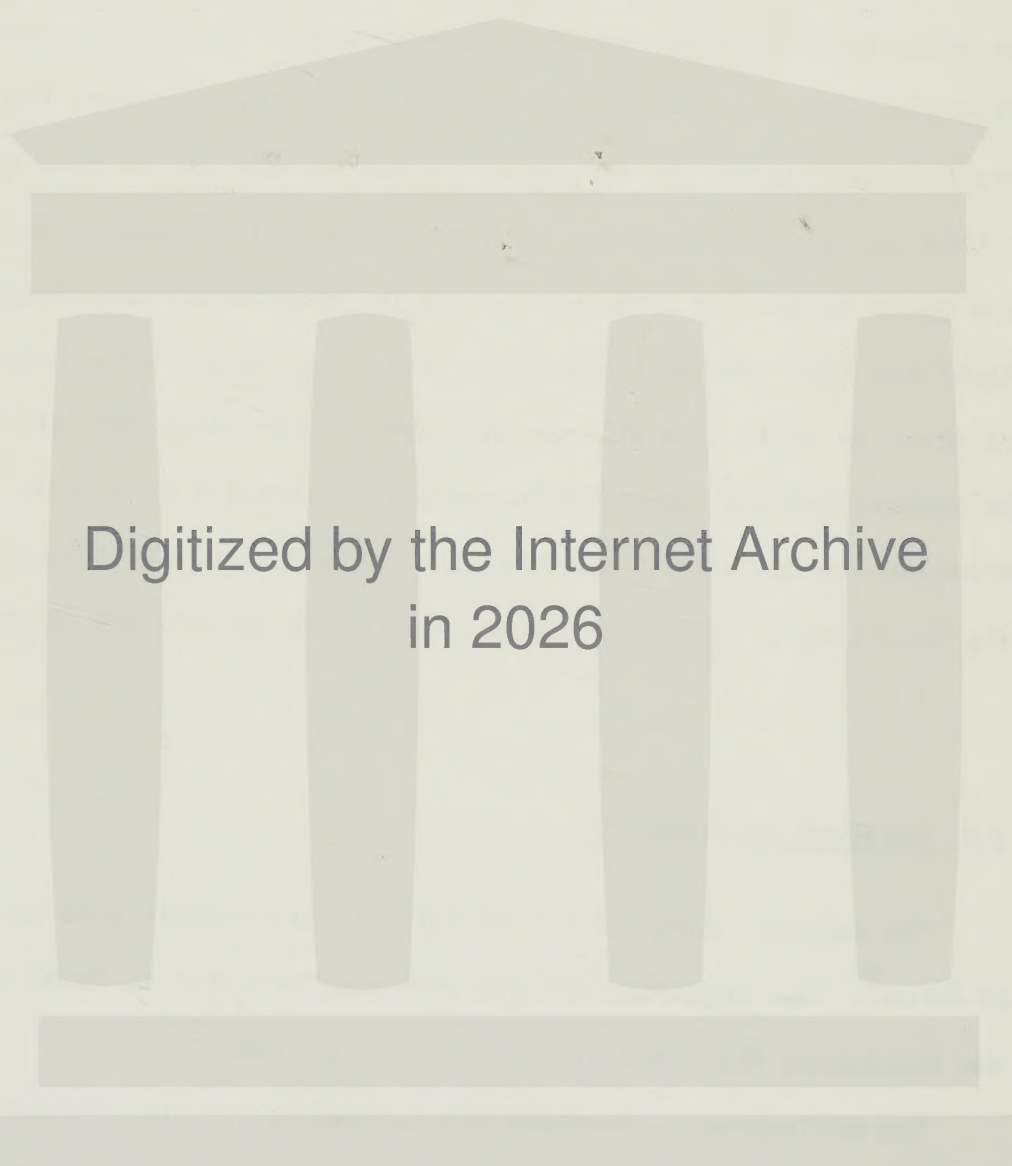
2.3. Gamma-gamma coincidences

A gamma-gamma coincidence experiment was performed using the technique described in ref. [10]. About $5 \cdot 10^5$ events were stored. Roughly 75% of these coincidence pairs could be assigned to the decay of ^{209}Rn , most of the remainder to the decay of the daughter, ^{209}At . Only one big (25 cm^3) and one small (1 cm^3) Ge(Li) detector were available during this experiment. The efficiency of the small detector is low for higher energies. The upper threshold for the energy was therefore set at $\sim 800 \text{ keV}$ in this channel. Up to this energy gates were set in the small detector channel. Higher energies were gated in the big detector channel in order to get coincidences between "high" and "low" energy transitions. The experimental coincidence intensities are given in table 3 as well as intensities calculated from the decay scheme. The intensities are expressed in percent and defined as in ref. [12]. Normalization has been made to fit the $338 \text{ keV} - 408 \text{ keV}$ coincidence intensity according to the decay scheme. Some gated spectra are shown in fig. 2a, b.

2.4. Electron spectroscopy

The detector used was a 2 mm thick Si(Li) crystal with an active area of 80 mm^2 . One spectrum recorded with this detector is found in fig. 3. The resolution was about 2.7 keV FWHM at 500 keV .

The K-electron intensities and deduced conversion coefficients are included in table 1. Fig. 4 shows experimental and theoretical [13] conversion coefficients. The normalization has been made assuming E2 character of the 408 keV transition. In a few cases limits could be established indicating E1 transitions.



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3. The decay scheme

A level scheme (see Fig. 5) was constructed using the coincidence information given in table 2 and sum relations. The computer code NUCLEV [14] was also used to find possible levels.

3.1. The levels at 408.3 and 745.8 keV

The strongest coincidence relation - 338-408 keV - indicates a level at 745.8 keV. It is further supported by the sum $337.5 + 408.3 = 745.8$ keV. As the 745.8 keV transition is not coincident with any of the 337.5 or 408.3 keV transitions it is placed to proceed to the ground state in parallel with the 337.5-408.3 cascade. The 408.3 keV transition is placed below the 337.5 keV transition because of its stronger intensity. The reversed order could not maintain the intensity balance. One may also note that the 408 keV transition is coincident with a number of transitions which have no coincidence relations to the 338 keV transition. Thus the data indicate two levels at 408.3 and 745.8 keV in agreement with the findings of ref. [6].

The transitions from these two levels are also in coincidence with the 511 peak. As no other coincidence relation with 511 keV quanta has been established, this might indicate β^+ feeding to the 408 and 746 keV levels. However, also (weak) branches to higher-lying levels may be involved, though not seen in the coincidences for intensity reasons.

3.2. The levels at 1097.7, 1953.5 and 2135.7 keV

Other relatively strong coincidences are those connecting the 408 keV and the 689, 856, and 1038 keV transitions. None of the latter are coincident with the 338 keV transition. It is therefore natural to interpret them as part of cascades including the 408 keV transition. The 689 - 856 keV and 689 - 1038 keV coincidences suggest levels at 1097.7, 1953.5, and 2135.7 keV. A reversed order would lead to negative intensity balance.

3.3. The 2414.9 keV level

The 279 keV gate shows coincidences with the 1038 - 689 - 408 keV cascade indicating a position on top of the 2136 keV level. We therefore suggest a level at 2414.9 keV. Sum relations give a connection to the 1953.5 keV level via the 461.6 keV transition.

3.4. The 794.6, 1081.2 and 1394.6 keV levels

Coincidences 279 - 673 - 408 keV indicates that the 673 keV transition is placed somewhere between the 2136 and 408 keV levels. The energy relation $2135.7 - 408.3 = 672.9 + 1054.5$ keV indicates a level at 1081.2 keV or at 1462.8 keV. The first alternative is preferred as the intensity of the 673 keV transition is twice that of the 1055 keV transition and no other transition seems to compensate the negative intensity balance for the second alternative. No coincidences 673 - 1055 keV are seen. This may be due to the regrettable fact that the experiment had to be performed with a modest coincidence efficiency in this energy range.

A level at 1081 keV also gives a sum relation: the 286.6 keV transition may connect the 1081 keV level and another level at 794.6 keV. The latter one is based on sum relations connecting it with the ground state as well as the 408, 1098 and 1954 keV levels via the 795, 386, 303, and 1159 keV transitions respectively. It is further supported by 386 - 408 keV coincidences.

The 1395 keV level is suggested on the basis of sum relations. The 297, 600, 986, and 1395 keV transitions may proceed to the levels at 1098, 795, 408, and 0 keV, respectively.

4. Spin and parity assignments

According to the shell model one should expect the ground state to have spin and parity $9/2^-$. The multipolarities deduced for the 338, 408,

and 746 keV transitions are consistent with the $7/2^-$ assignment made by ref. [6]. It is tentatively accepted here as a very probable alternative.

The levels at 1954, 2136, and 2415 keV seem to have positive parity. The limits of the conversion coefficients for the 856 and 1038 keV transitions indicate E1 multipolarity. The M1 character of the 279 and 462 keV transitions supports that the three levels mentioned have the same parity. However, data are too meagre to permit any definite spin assignments.

5. The electron capture and positron feeding

In this case an estimation of $\log ft$ values is uncertain for at least two reasons: 1) The available information on the Q_β value is given with quite big errors [15]: (3950 ± 1000) keV. 2) The relatively high Q_β value offers a great number of levels to be populated in the decay. Several weak branches may change the intensity balance considerably.

An estimate of the EC decay intensity has been done (cf ref. [11]). The K_{α_1} X-ray peak has the intensity 121, normalized to the scale used in table 1. The contribution from contamination has been subtracted. Correcting for fluorescent yield (0.96) and $K_{\alpha_1}/K_{\text{tot}}$ ratio (0.493) one gets an intensity of 246 from vacancies in the K-shell due to K-conversion. K-conversion intensities are taken from table 1. If one assumes the L-capture to be 1/8 of K-capture one gets a decay intensity of 278 estimated from the K_{α_1} -peak intensity.

Summing the total intensity feeding the ground state one finds an intensity of 159 included in the decay scheme, that is, 57% of the total electron capture decay. It is assumed that only a negligible branch proceeds directly to the $^{209}_{85}\text{At}_{124}$ ground state in the decay of $^{209}_{86}\text{Rn}_{123}$. From systematics one expects spins $9/2^-$ and $5/2^-$ for the ground states which would lead to a high $\log ft$ value.

The 408 keV gamma transition therefore occurs in 32% of the ^{209}Rn decays. Correction for an alpha branch of 17% has been made.

The calculation above shows that about 43% of the EC-intensity is not included in the decay scheme. One has to bear this "hidden" intensity in mind when logft values are discussed here. The two $(7/2^-)$ -states at 408 keV and 746 keV show logft values of 6.8 and 6.4, respectively, if corrections are made as sketched above. One may also estimate limits of positron branches to these states ($\gtrsim 1.9$ and $\gtrsim 1.3\%$) with logft values $\gtrsim 7$. This may be compared with ^{207}Bi where the electron capture and positron branches to the 742 and 992 keV states proceed with logft = 7.4 and 6.5 respectively.

Logft $\gtrsim 6.9$ is calculated for the three positive parity states in ^{209}At . This is similar to the logft values of positive parity states in odd-A Bi isotopes. However, even small changes in the decay scheme of ^{209}Rn might influence the logft values.

6. Discussion

6.1. The 746 and 408 keV states

It has been proposed [6], on the basis of transition probabilities, that the 408 keV level would be a state of essentially $f_{7/2}$ character and the 746 keV state a member of the $(h_{9/2}^3)$ configuration. It is not obvious that the single particle state could be pushed down from 674 keV [4] in ^{211}At to only 408 keV in ^{209}At . In the isotone ^{207}Bi the same level is found at 992 keV. This state has been found to contain [1] roughly one order of magnitude stronger contribution of $\pi f_{7/2}$ than the $7/2^-$ level of 742 keV.

The $7/2^-$ 674 keV state in ^{211}At is depopulated to the ground state via an M1 + E2 transition [4] while the 866 keV level $(7/2^-)$, assigned $(h_{9/2}^3)_{7/2}$ nature, is connected to the $9/2^-$ ground state by an E2 transition. This is in accordance with theory claiming that M1 transitions are for-

an M1 transition connecting the 746 keV level and the ground state while the 408 keV level is feeding the ground state via an E2 transition. We therefore prefer the $\pi f_{7/2}$ interpretation for the 746 keV state, keeping the excitation energy approximately constant in $^{211}, ^{209}\text{At}$. This would lead to similar energy shifts for the two levels when going from ^{207}Bi to ^{209}At . Also the logft values seem to favour this description, with a slower transition to the lower level. The 408 keV level would then essentially be due to $(h_{9/2}^3)_{7/2^-}$ or $[(h_{9/2}^3) + (2^+)_v]$ configurations. It is known that $j = J - 1$ states tend to appear at very low energies. The same effect is seen in $7/2^+$ states of Ag isotopes [16] where, according to interpretations, important components of $\pi(g_{9/2}) + \text{phonon}$ character are present in the wave functions.

6.2. The positive parity states

Unfortunately the experimental data do not permit any definite spin assignments for the levels at 2415, 2136, and 1954 keV. The positive parity, however, is relatively well established for these levels. They seem to be fed directly in the beta decay. However, according to estimations only 57% of the beta decay intensity is included in the scheme. Unplaced transitions may therefore change the intensity balance.

The ^{209}Rn nucleus is expected, for systematic reasons, to have spin $5/2^-$ in the ground state. One would find first forbidden transitions only to $3/2^+$, $5/2^+$, and $7/2^+$ states. Such transitions have earlier been explained as due to a transformation of a $d_{3/2}$ or $d_{5/2}$ proton below the $Z = 82$ shell closure into a neutron state below $N = 126$ closure [2, 3]. In ^{209}Rn the states are filled up to the $5/2$ neutron state with one hole in this state. Therefore $\pi d_{3/2} \rightarrow \nu f_{5/2}$ and $\pi d_{5/2} \rightarrow \nu f_{5/2}$ transitions could be expected, leaving a proton hole in the $d_{3/2}$ or $d_{5/2}$ states.

In ^{207}Bi a $3/2^+$ state is found [1, 5] at 2060 keV and a $5/2^+$ state at 2405 keV which have been interpreted in these terms. Below these states a $1/2^+$ level appears, consequently taken as a state arising from an $s_{1/2}$ proton hole.

If the 1954 keV level in ^{209}At is populated directly in the electron capture process one would tentatively assign spin $3/2^+$ to it and $5/2^+$ to the 2136 keV level. A $1/2^+$ state would be expected below the $3/2^+$ level. No such state could be established in this experiment. One cannot exclude the possibility that transitions from higher levels may change the intensity balance to zero. If so, the 1954, 2136, and 2415 keV states could be given the spins $1/2^+$, $3/2^+$, and $5/2^+$, respectively. This would make the agreement with the corresponding excitation energies in ^{207}Bi even closer.

Acknowledgement

We are indebted to colleagues in the ISOLDE collaboration, in particular to the isotope separator crew. We also wish to thank Prof. G. Andersson for his continuous interest and support. The work was financially supported by the Swedish Atomic Research Council.

References

- 1) Astner, G. and Alpsten, M., Nucl. Phys. A140, 643 (1970).
- 2) Alpsten, M. and Astner, G., Nucl. Phys. A134, 407 (1969).
- 3) Alpsten, M. and Astner, G., Physica Scripta 5, 41 (1972).
- 4) Astner, G., Physica Scripta 5, 31 (1972).
- 5) Arbman, E., Burde, J. and Gerholm, T.R., Ark. Fys. 13, 501 (1958).
- 6) Kempisty, T., Morek, T., Peker, L.K., Petrozolin, K. and Chojnacki, S.,
Dubna preprint, P6 - 5878 (1971).
- 7) Lederer, C.M., Hollander, J.M. and Perlman, I., Table of Isotopes,
Wiley, New York, 1967.
- 8) Jonson, B., Alpsten, M., Appelqvist, Å. and Astner, G., Nucl. Phys.
A174, 225 (1971).
- 9) The ISOLDE collaboration, ed. Kjelberg, A. and Rudstam, G.,
CERN Report 71 - 3 (1970).
- 10) Jonson, B., Alpsten, M., Appelqvist, Å., Bengtsson, B. and
Johansson, K.A., Physica Scripta 7, 147 (1973).
- 11) Alpsten, M., Appelqvist, Å. and Astner, G., Physica Scripta 4,
137 (1971).
- 12) Wapstra, A.H., Ch. VIII C in Alpha-Beta- and Gamma-ray Spectroscopy
(ed. Siegbahn, K.) North Holland Publ. Co., Amsterdam (1965).
- 13) Hager, R.S. and Seltzer, E.C., Nuclear Data A4, 1 (1968).
- 14) Helmer, G. and Bäcklin, A., Nucl. Instr. and Meth. 65, 31 (1968).
- 15) Mattauch, J.H.E., Thiele, W. and Wapstra, A.H., Nucl. Phys. 67, 1 (1965).
- 16) Paar, V., Physics Letters 39B, 587 (1972).

Table 1. Transitions in the decay of ^{203}Rn . Errors represent two standard deviations.

Transition energy, keV	Gamma intensity	Total intensity	Internal conversion coefficient	K-conversion coefficient	Multipolarity assignment
182.3 $\pm$ 0.1	0.5 $\pm$ 0.1				
212.2 $\pm$ 0.1	2.3 $\pm$ 0.2	3.9 $\pm$ 0.3	1.7 $\pm$ 0.4	2.0 $\pm$ 0.3	E1
226.6 $\pm$ 0.1	0.7 $\pm$ 0.1				
303.1 $\pm$ 0.1	1.1 $\pm$ 0.1	1.7 $\pm$ 0.1	0.5 $\pm$ 0.1	0.4 $\pm$ 0.1	E1
337.5 $\pm$ 0.1	29 $\pm$ 2	40 $\pm$ 5	9.2 $\pm$ 0.3	0.3 $\pm$ 0.03	E1
380.9 $\pm$ 0.1	1.0 $\pm$ 0.1				
386.3 $\pm$ 0.1	4.1 $\pm$ 0.4	5.0 $\pm$ 0.5	0.8 $\pm$ 0.3	0.2 $\pm$ 0.1	E1
408.3 $\pm$ 0.1	100	106	3.6 $\pm$ 0.2	0.036 ^{a)}	E2
461.6 $\pm$ 0.1	2.7 $\pm$ 0.3	3.4 $\pm$ 0.4	0.5 $\pm$ 0.2	0.2 $\pm$ 0.1	E1
577.2 $\pm$ 0.1	1.4 $\pm$ 0.2				
599.9 $\pm$ 0.1	0.6 $\pm$ 0.2 ^{b)}				
672.9 $\pm$ 0.1	5.9 $\pm$ 0.5	6.0 $\pm$ 0.5	< 0.1	< 0.02	(E1), E2
684.6 $\pm$ 0.1	2.4 $\pm$ 0.2	2.6 $\pm$ 0.2	0.2 $\pm$ 0.1	0.08 $\pm$ 0.06	E1
689.4 $\pm$ 0.1	18.3 $\pm$ 1.4	19.7 $\pm$ 0.5	1.1 $\pm$ 0.2	0.06 $\pm$ 0.02	E1
722.8 $\pm$ 0.1	0.8 $\pm$ 0.1				
745.8 $\pm$ 0.1	43 $\pm$ 3	45 $\pm$ 3	1.8 $\pm$ 0.2	0.04 $\pm$ 0.01	E1
794.6 $\pm$ 0.1	5.5 $\pm$ 0.5				
855.8 $\pm$ 0.1	8.3 $\pm$ 0.7		< 0.06	< 0.007	E1
986.1 $\pm$ 0.1	1.1 $\pm$ 0.1				
1038.0 $\pm$ 0.1	8.0 $\pm$ 0.7		< 0.04	< 0.005	E1
1054.5 $\pm$ 0.1	3.0 $\pm$ 0.3				
1059.3 $\pm$ 0.1	0.9 $\pm$ 0.2				
1065.6 $\pm$ 0.1	3.2 $\pm$ 0.3				
1158.9 $\pm$ 0.1	1.4 $\pm$ 0.2				
1187.0 $\pm$ 0.1	0.8 $\pm$ 0.1				
1341.9 $\pm$ 0.1	0.9 $\pm$ 0.2				
1394.6 $\pm$ 0.1	1.9 $\pm$ 0.2				
1543.3 $\pm$ 0.1	1.5 $\pm$ 0.2				

a) Used for normalization

b) Corrected for contribution from ^{205}Po decay

Table 2. Transitions assigned to the ^{209}Rn decay with less certainty.

Transition energy keV	Gamma intensity
185.3 ± 0.1	0.5 ± 0.1
257.0 ± 0.2	0.6 ± 0.2
291.0 ± 0.1	0.3 ± 0.1
357.4 ± 0.1	0.4 ± 0.1
364.7 ± 0.1	0.3 ± 0.1
705.3 ± 0.1	0.4 ± 0.1
761.5 ± 0.1	1.0 ± 0.2
1097.6 ± 0.2	0.5 ± 0.1

Table 3. Coincidence intensities. Normalization has been done on the 338-408 keV coincidences. Cases where data are available from only one gate, have been marked with a star. For other experimental intensities the mean of two reciprocal values are given. Errors represent two standard deviations.

E_1	E_2	I_{exp}	I_{scheme}
279	408	1.6 ± 0.7	1.4
	673	1.5 ± 0.9	0.5
	689	$(0.8 \pm 0.6)^*$	1.3
	1038	2.5 ± 0.9	1.6
338	408	26.8	26.8
	511	2.7 ± 1.2	
386	408	2.6 ± 1.2	3.9
408	462	2.3 ± 1.4	2.1
	511	11 ± 3	
	673	6.9 ± 3.0	5.6
	689	17 ± 4	17
	856	11 ± 3	7.2
	1038	8 ± 3	7.1
	1055	4 ± 2	2.6
689	856	$6 \pm 5^*$	7.1
	1038	7 ± 5	6.8
746	511	5 ± 3	

Figure captions

Fig. 1. Gamma-ray spectrum (energy range 100 - 2000 keV) from the decay of ^{209}Rn . Contaminations are indicated:

x : ^{209}At

⊙ : ^{208}At

Δ : ^{205}Po

+ : ^{204}Po

s : shortlived ($T_{1/2}$ significantly shorter than that of ^{209}Rn).

Not identified.

Transitions within parentheses are not well established to belong to the ^{209}Rn decay.

Fig. 2. Spectra from the coincidence experiment. The background is subtracted.

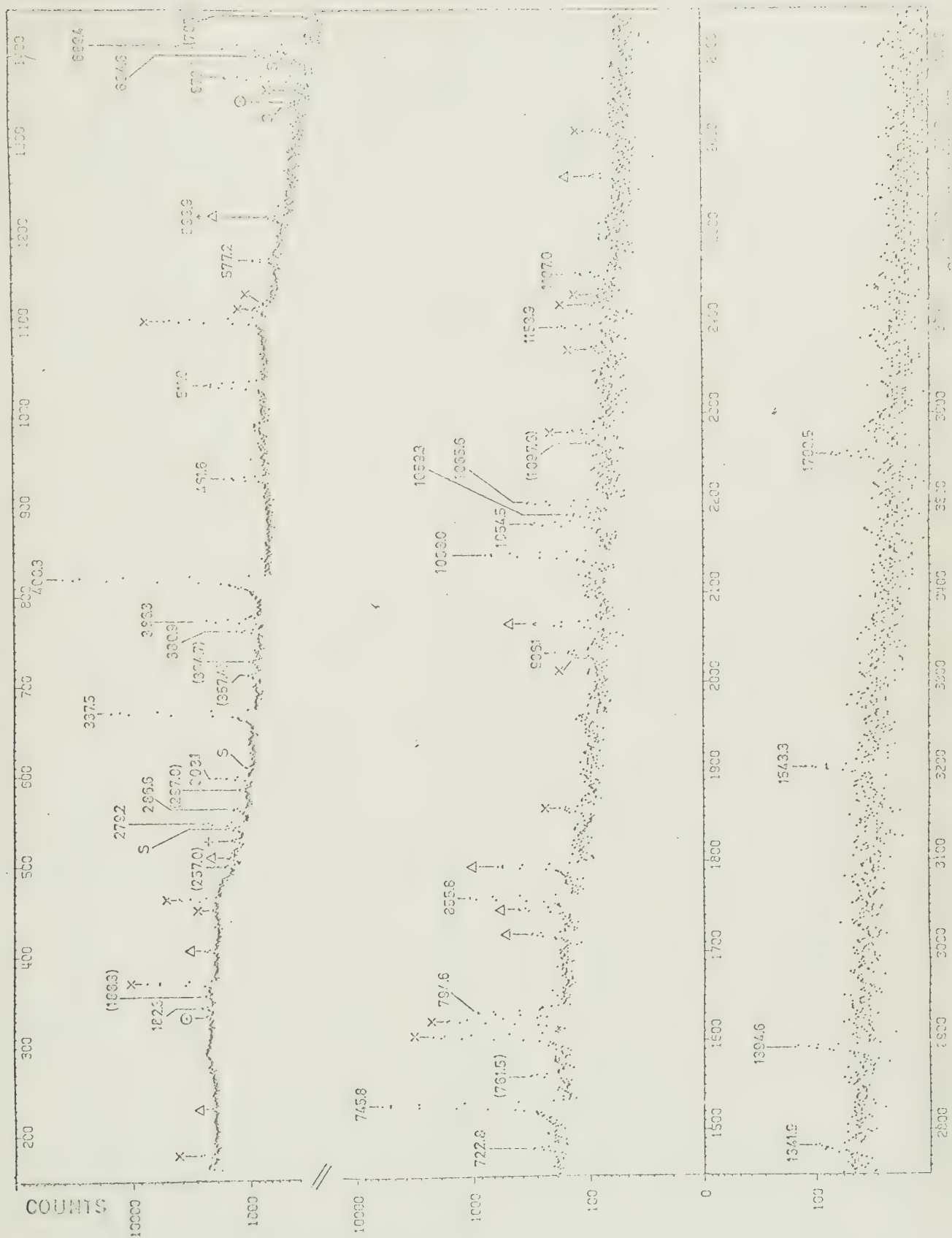
a) Gates set at 338 and 408 keV in the small detector channel.

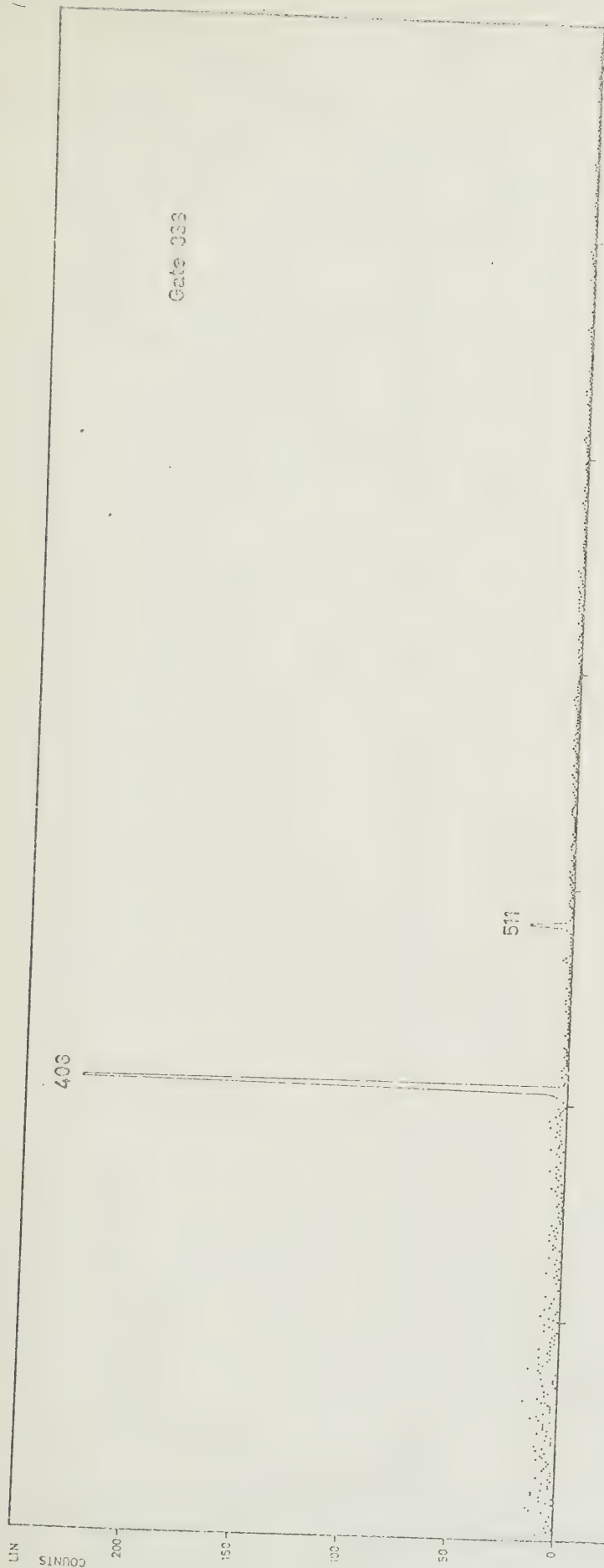
b) Gate set at 1038 keV in the big detector channel.

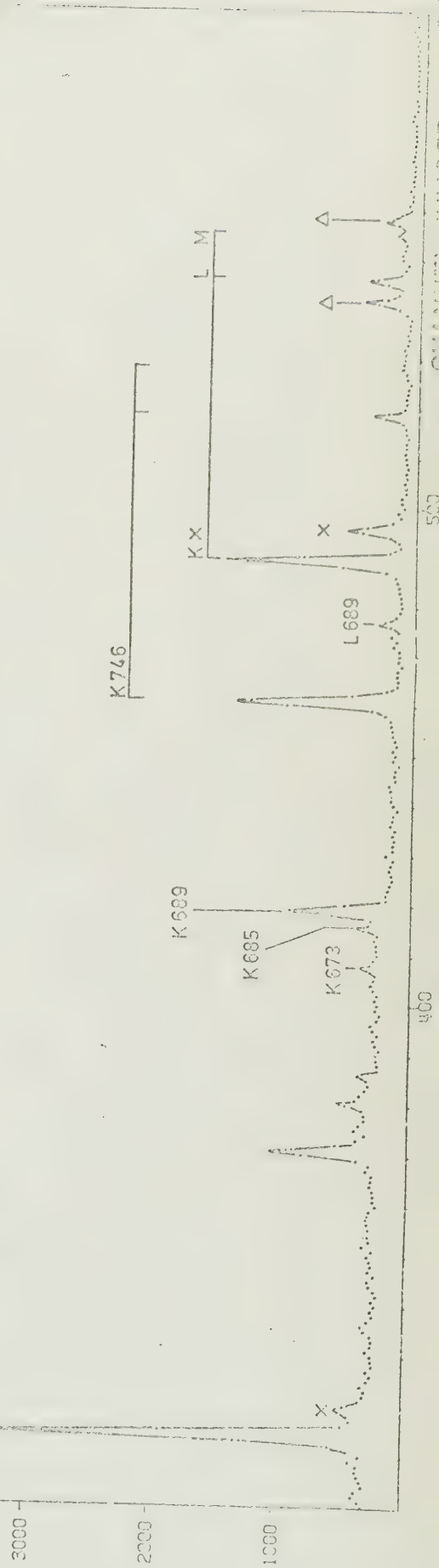
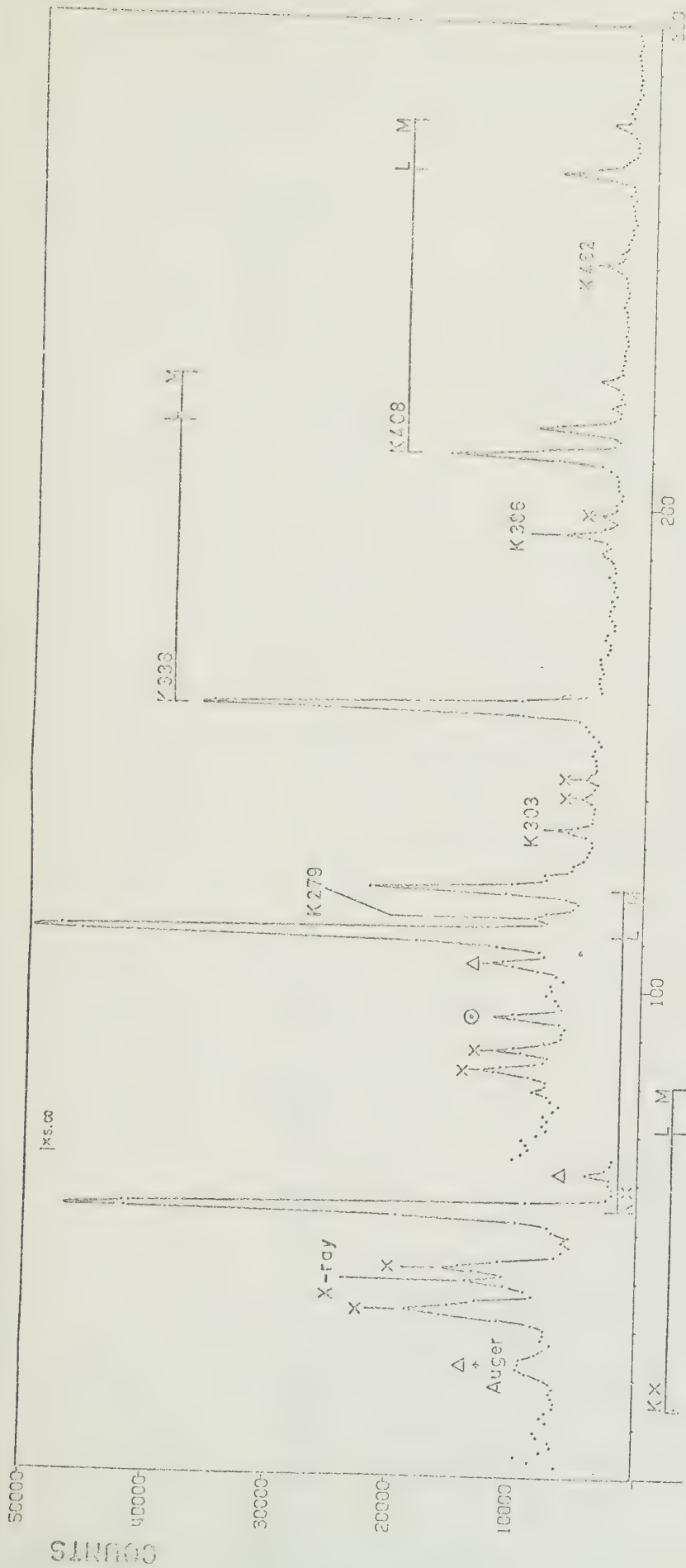
Fig. 3. Electron spectrum recorded with a 2 mm thick Si(Li) detector for energies 50 - 1000 keV. (The same symbols as in fig. 1.).

Fig. 4. Internal K-conversion coefficients. Experimental points are from table 1. The lines represent theoretical values from ref. [13].

Fig. 5. The level scheme of ^{209}At as seen in the decay of ^{209}Rn . Branching ratios and logft values are indicated to the right of the levels. The branching ratios have been normalized to give 100% for the total β-decay. (See discussion in §5.) Logft values should be regarded as lower limits.







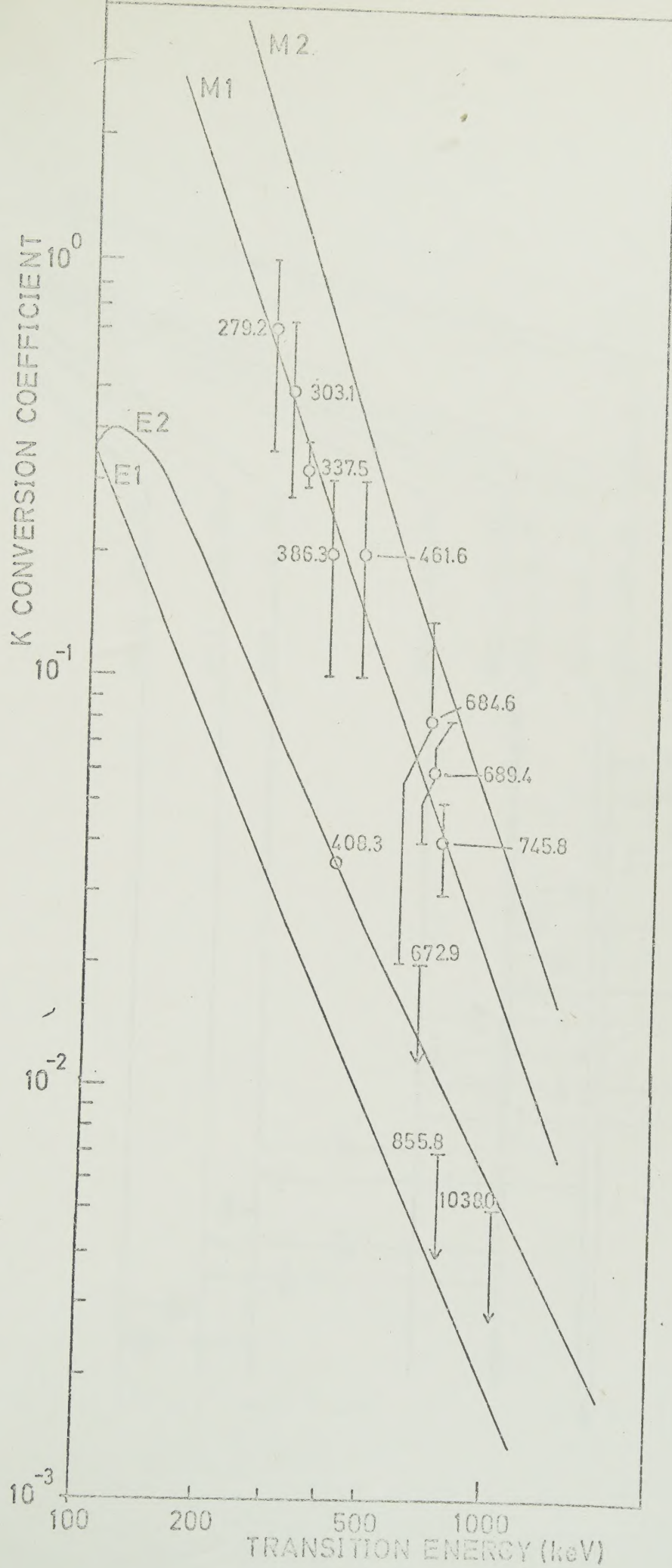


Fig. 4.

